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Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Ultra-high neutrino fluxes as a probe for non-standard physics

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UHE NEUTRINOS AND THE GLASHOW RESONANCE

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NuSKY, ICTP, June 25, 2011

The Glashow Resonance....

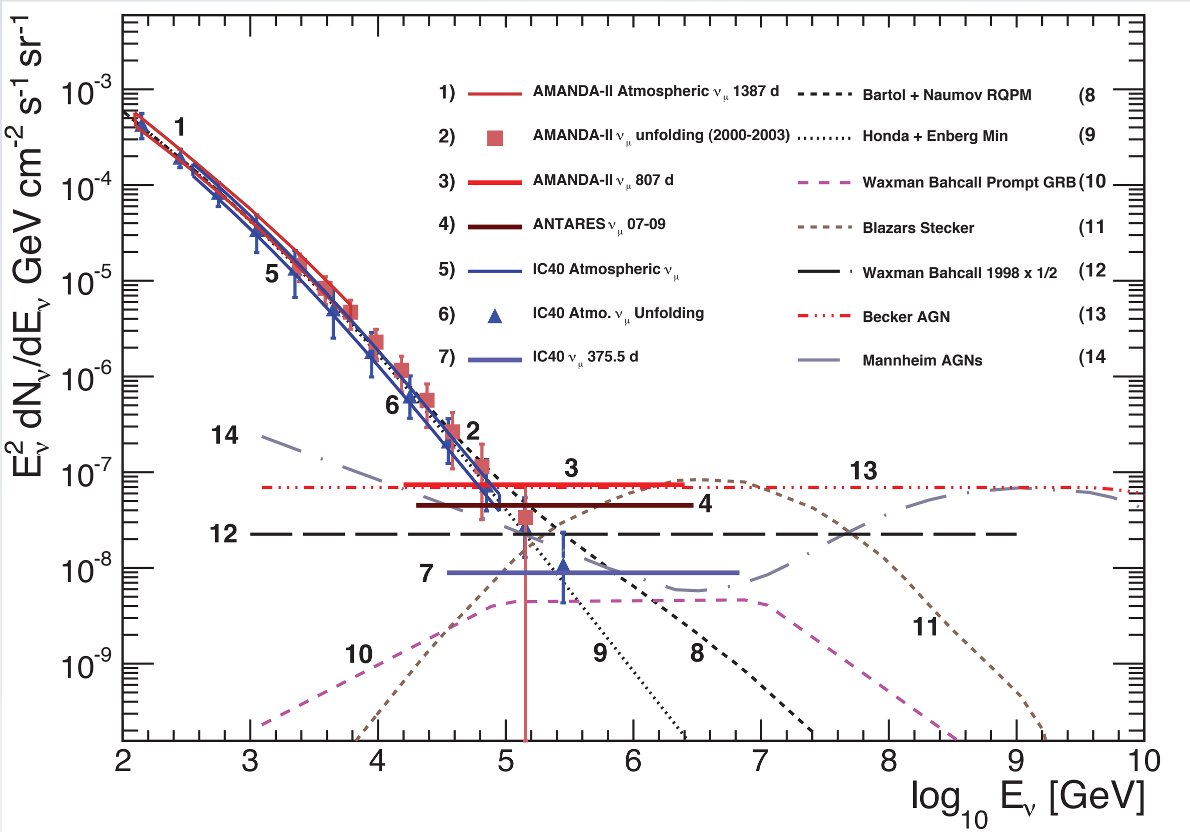
The Glashow Resonance (GR) refers to the Standard Model process which results in the resonant formation of an intermediate W^- in $\bar{\nu}_e e$ at E_nu = 6.3 PeV.

Glashow '60, Berezinsky and Gazizov, '77

- The final states could be to leptons or hadrons, giving both showers and muon or tau lepton tracks in UHE detectors.

- While usually dwarfed by the neutrino-nucleon cross-section, the anti-neutrino-electron cross-section at the GR is higher than the neutrino-nucleon cross-section at all energies upto 10^21 eV.

The Glashow Resonance....why it could be important



Icecube
arXiv:1104.5187

The region where an extra-galactic UHE flux emerges above the atmospheric background but stays below current IC bounds is in the neighbourhood of the GR

The Glashow Resonance....

Due to these reasons, it could be useful to look carefully at this small but important region.

Additionally, it could be useful to identify events with unique signatures and low backgrounds in its neighbourhood.

Could it be used as a tool to see X-galactic diffuse neutrino signals?

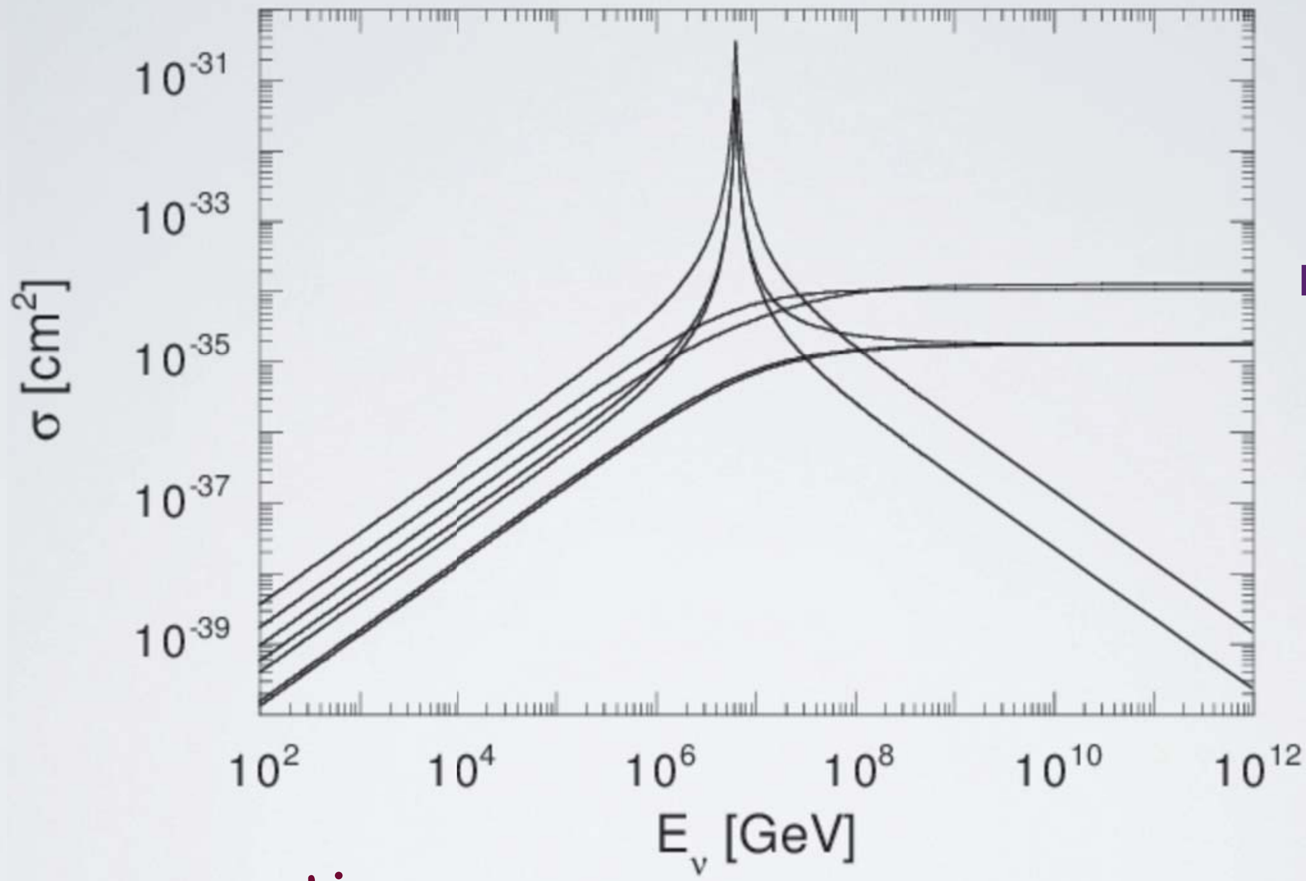
GR Xsecs.....

$$\frac{d\sigma(\bar{\nu}_e e \to \bar{\nu}_\mu \mu)}{dy} = \frac{G_F^2 m E_\nu}{2\pi} \frac{4(1-y)^2[1-(\mu^2-m^2)/2mE_\nu]^2}{(1-2mE_\nu/M_W^2)^2 + \Gamma_W^2/M_W^2}$$

$$\frac{d\sigma(\bar{\nu}_e e \to \text{ hadrons})}{dy} = \frac{d\sigma(\bar{\nu}_e e \to \bar{\nu}_\mu \mu)}{dy} \cdot \frac{\Gamma(W \to \text{ hadrons})}{\Gamma(W \to \mu \bar{\nu}_\mu)}$$

Lab frame, m= electron mass, y= E_mu/E_nu

Neutrino Cross-sections at the Glashow Resonance



RG, Quigg, Reno and Sarcevic

The cross-sections

$\bar{\nu}_e e \rightarrow \mathrm{hadrons}$, $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$, $\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu$, $\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau$ are resonant

The Glashow Resonance.......Relevant Cross-sections

Reaction	σ [cm^2]
$\nu_\mu e \to \nu_\mu e$	5.86×10^{-36}
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	5.16×10^{-36}
$\nu_\mu e \to \mu \nu_e$	5.42×10^{-35}
$\nu_e e \to \nu_e e$	3.10×10^{-35}
$\bar{\nu}_e e \to \bar{\nu}_e e$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\mu \mu$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\tau \tau$	5.38×10^{-32}
$\bar{\nu}_e e \to$ hadrons	3.41×10^{-31}
$\bar{\nu}_e e \to$ anything	5.02×10^{-31}
$\nu_\mu N \to \mu^- +$ anything	1.43×10^{-33}
$\nu_\mu N \to \nu_\mu +$ anything	6.04×10^{-34}
$\bar{\nu}_\mu N \to \mu^+ +$ anything	1.41×10^{-33}
$\bar{\nu}_\mu N \to \bar{\nu}_\mu +$ anything	5.98×10^{-34}

RG, Quigg, Reno and Sarcevic '95

We note that, at the GR........

$$\frac{\bar{\nu}_e e \to anything}{\nu_\mu + N \to \mu + anything} \approx 360$$

standard CC process total

$$\frac{\bar{\nu}_e e \to hadrons}{\nu_\mu + N \to \mu + anything} \approx 240$$

pure muon track, unique if contained initial vertex

$$\frac{\bar{\nu}_e e \to \bar{\nu}_\mu \mu}{\nu_\mu + N \to \mu + anything} \approx 40$$

pure tau track, unique if contained lollipop

$$\frac{\bar{\nu}_e + e \to \bar{\nu}_\mu + \mu}{\nu_\mu + e \to \mu + \nu_e} \approx 1000$$

background to pure muon with contained initial vertex

Detecting the GR..........

- Earlier studies have focussed on its detection via shower events and on how the GR can be used as a discriminator of the relative abundance of pp vs p-gamma sources

Learned and Pakvasa ‘95, Anchordoqui, Goldberg, Halzen and Weiler ‘05, Bhattacharjee and Gupta ‘05, Maltoni and Winter ‘08, Hummer, Maltoni, Winter and Yaguna ‘10, Xing and Zhou ’11

We study here its potential as a discovery channel for UHE neutrinos, using both showers and lepton tracks

The Generalized UHE Neutrino Flux...........

Parametrize the flux at source as

$$\Phi_{\rm source} = x\Phi^{pp}_{\rm source} + (1-x)\Phi^{p\gamma}_{\rm source}.$$

- Standard oscillations with tribimaximal mixing give

$$\Phi^{pp}_{\rm earth} \propto \underbrace{\begin{pmatrix}1\\1\\1\end{pmatrix}}_{\nu} + \underbrace{\begin{pmatrix}1\\1\\1\end{pmatrix}}_{\bar{\nu}},$$

$$\Phi^{p\gamma}_{\rm earth} \propto \underbrace{\begin{pmatrix}0.78\\0.61\\0.61\end{pmatrix}}_{\nu} + \underbrace{\begin{pmatrix}0.22\\0.39\\0.39\end{pmatrix}}_{\bar{\nu}}.$$

Generalized source fluxes..........

Using the IC Apr 2011 bound as a benchmark flux, we have, for the sum of all species,

$$E_\nu^2 \Phi_{\nu+\bar{\nu}} \;=\; 2\times 10^{-8} \epsilon_\pi \xi_z \quad (\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}),$$

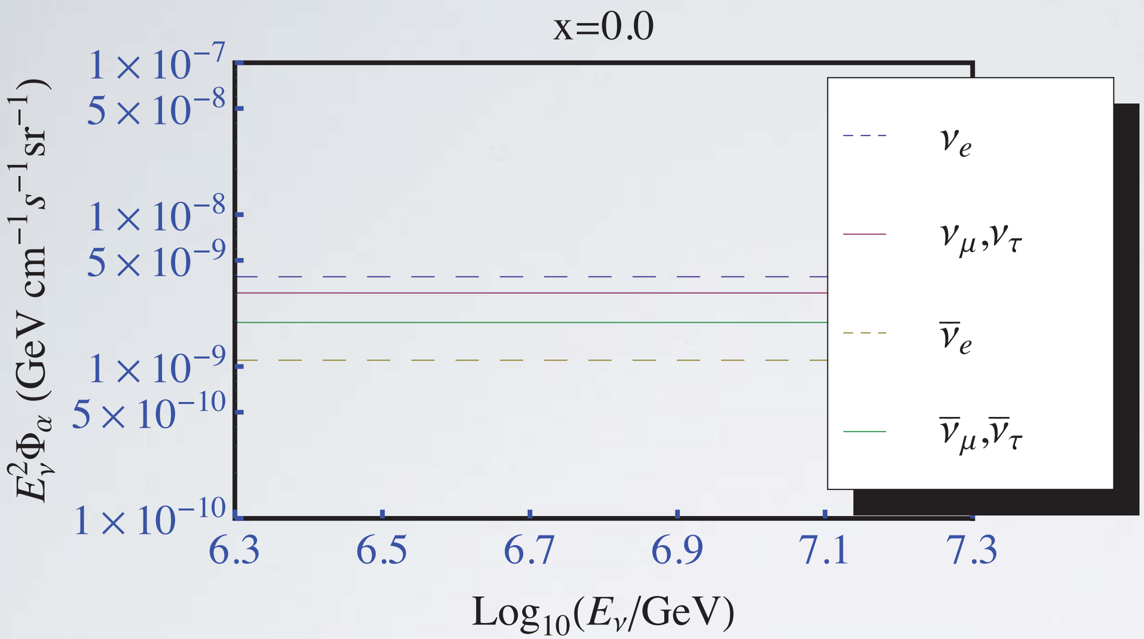
with

$$\Phi_{\nu_e} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.78}{3}\cdot 0.25\right]\frac{1}{E_\nu^2},$$

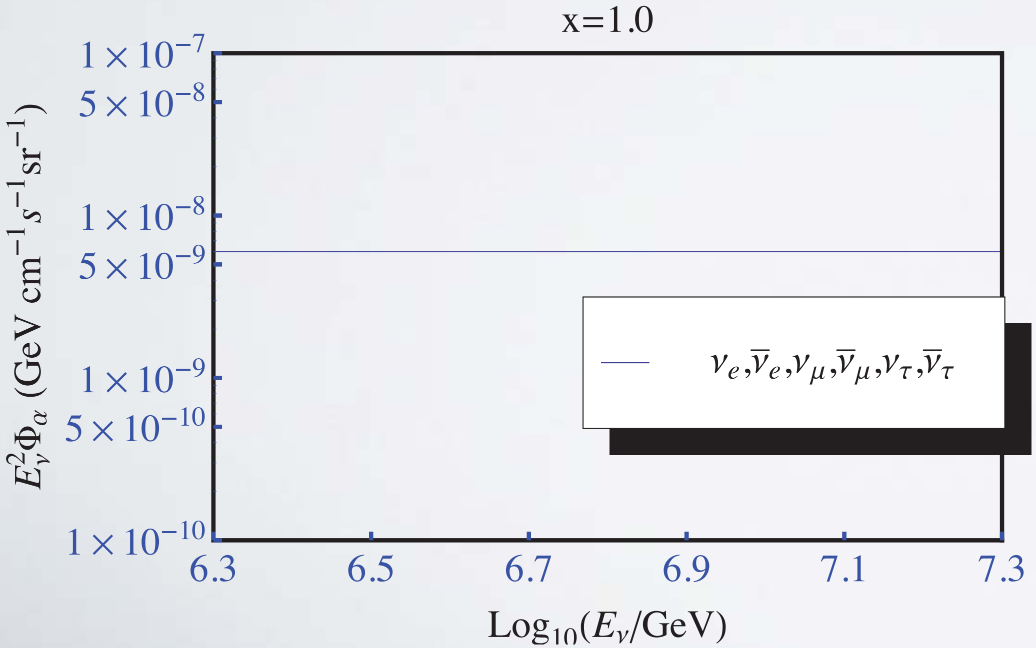
$$\Phi_{\nu_\mu} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.61}{3}\cdot 0.25\right]\frac{1}{E_\nu^2} = \Phi_{\nu_\tau},$$

$$\Phi_{\bar{\nu}_e} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.22}{3}\cdot 0.25\right]\frac{1}{E_\nu^2},$$

$$\Phi_{\bar{\nu}_\mu} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.39}{3}\cdot 0.25\right]\frac{1}{E_\nu^2} = \Phi_{\bar{\nu}_\tau}.$$



Fluxes hierarchical for p-gamma, democratic for pp sources



Mu and tau fluxes always equal for both neutrinos and anti-neutrinos irrespective of x for tribimaximal mixing

Shower events in the neighbourhood of the GR...

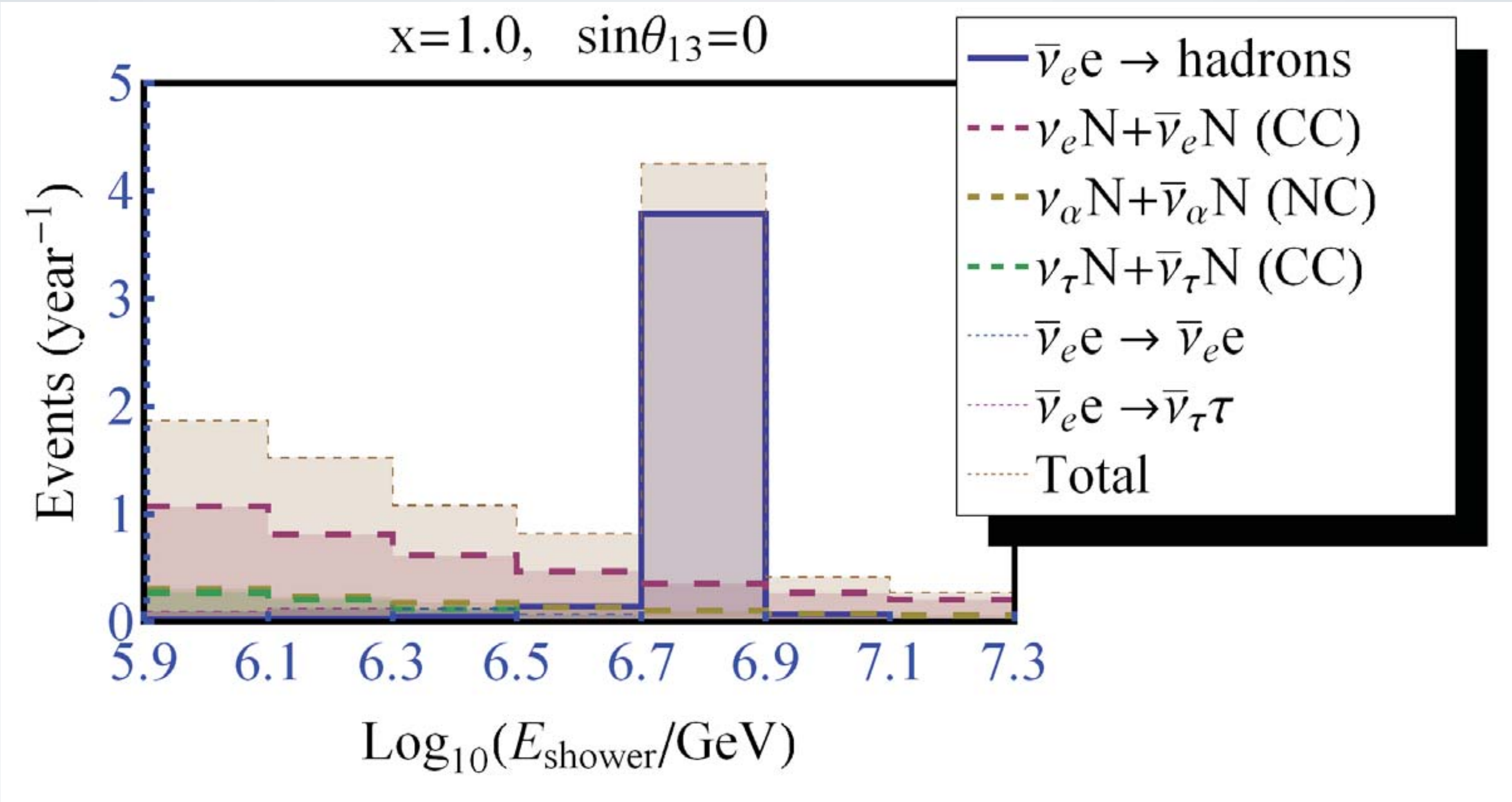
Resonant Events....

- $\bar{\nu}_e e \to \text{hadrons}$
- $\bar{\nu}_e e \to \bar{\nu}_e e$
- $\bar{\nu}_e e \to \bar{\nu}_\tau \tau$

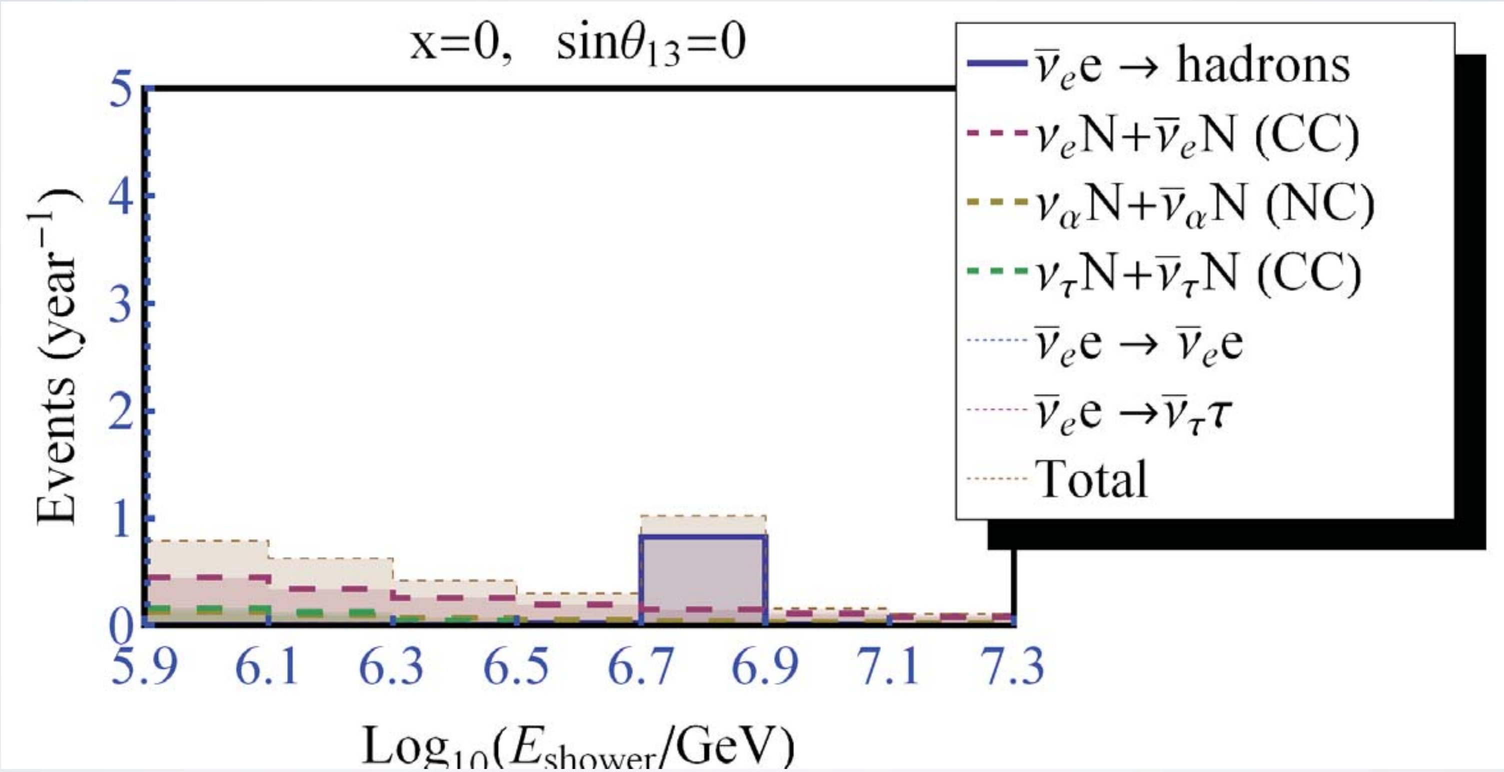
Non-Resonant Events....

- $\nu_e N + \bar{\nu}_e N \ (\text{CC})$
- $\nu_\tau N + \bar{\nu}_\tau N \ (\text{CC})$
- $\nu_\alpha N + \bar{\nu}_\alpha N \ (\text{NC})$

Shower and GR events for pp sources.....



Shower and GR events for p-gamma sources.....



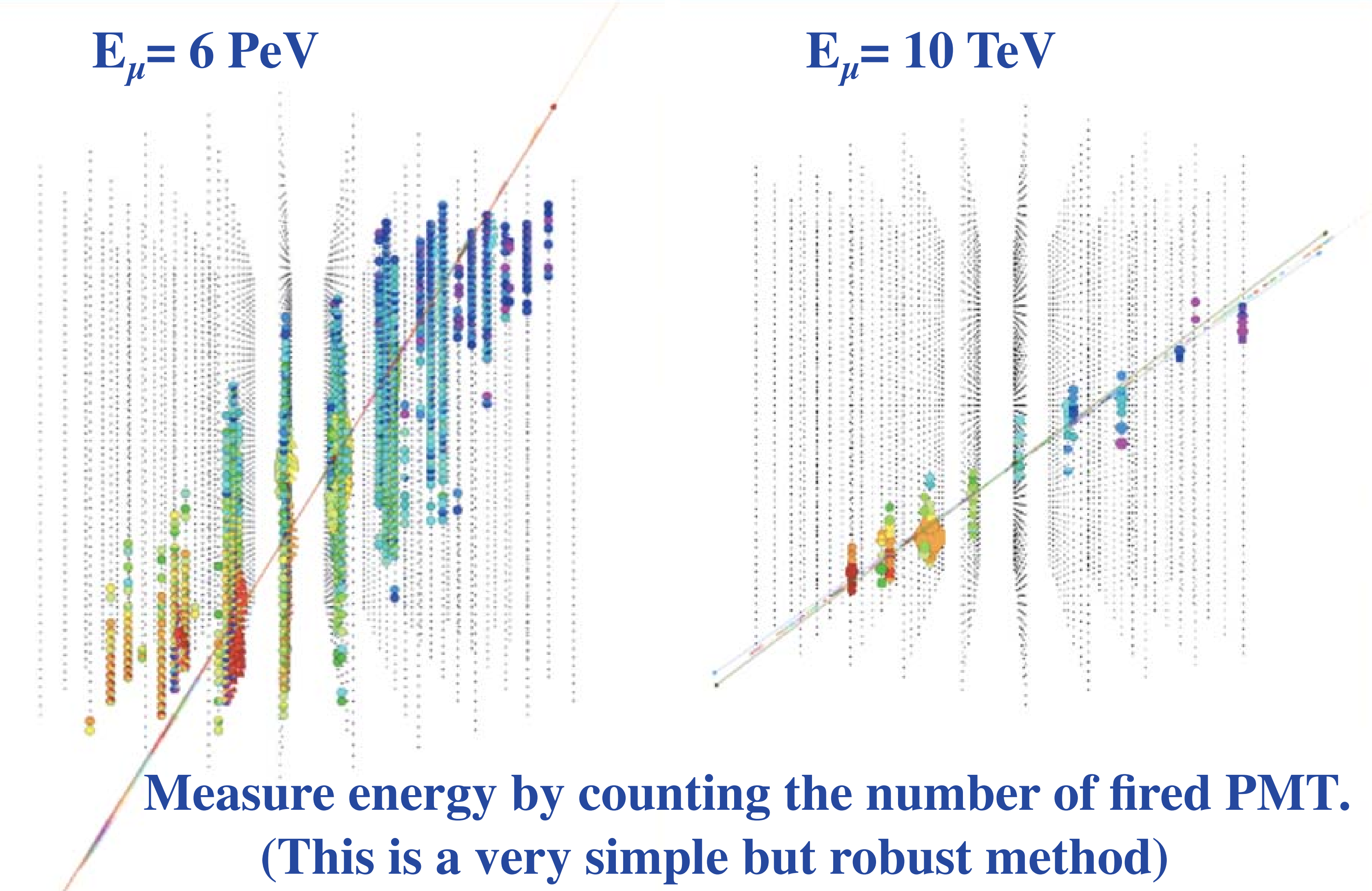
Pure Lepton Tracks at the GR.............

In addition to showers, the following processes are resonant and also have distinctive signatures

- $\bar{\nu}_e e \to \bar{\nu}_\mu \mu$ pure muon track with contained vertex and nothing else
- $\bar{\nu}_e e \to \bar{\nu}_\tau \tau$ lollipop with contained vertex

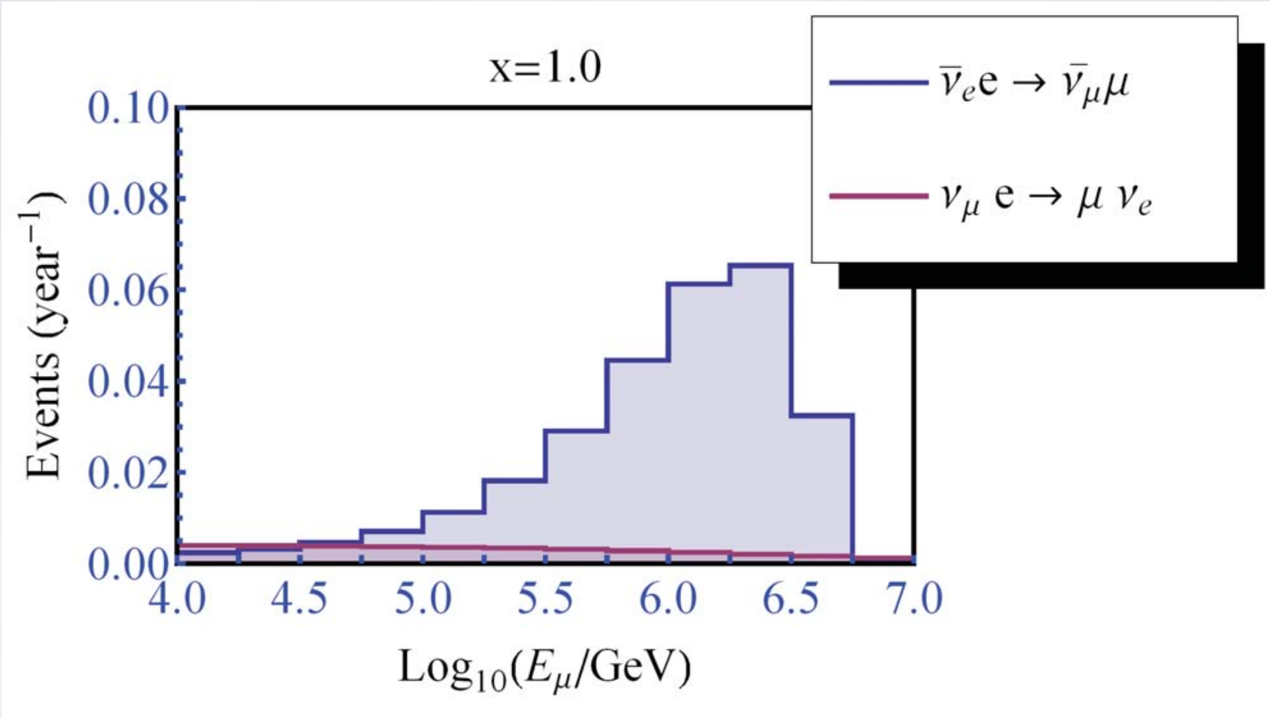
Add them to signal calculation for GR

Muon Events



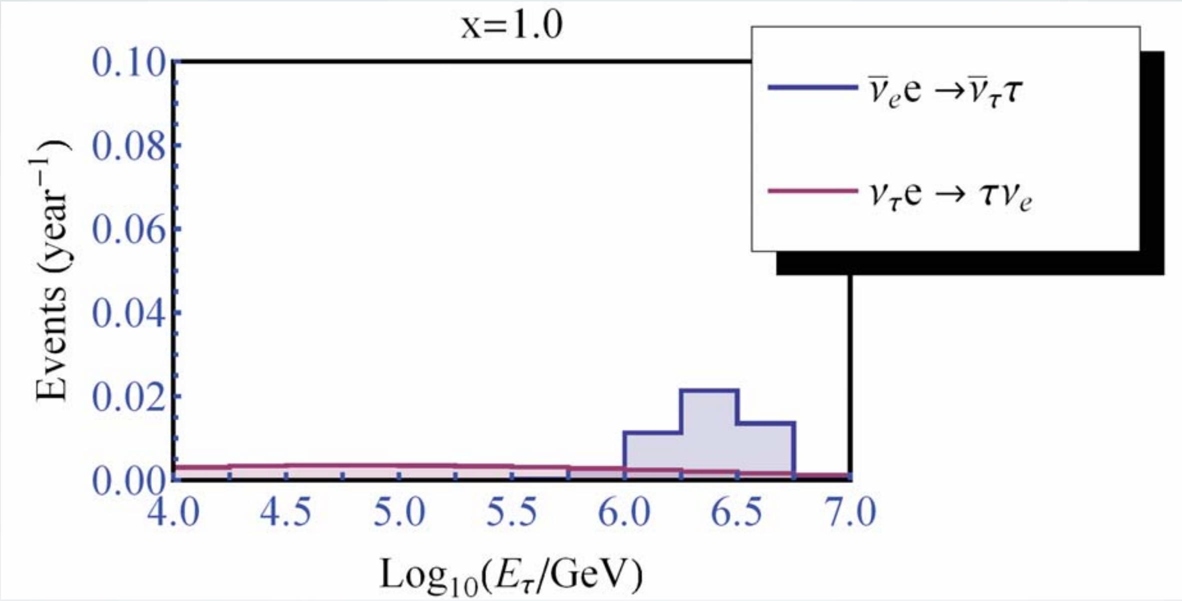
Measure energy by counting the number of fired PMT.
(This is a very simple but robust method)

Pure muons at the GR..............



Pileup of muons in bins below GR energy , dictated by rapidity distribution...........

Contained Lollipops at the GR............



Once tau decay is put in, number of events is small, but have a distinctive topology and negligible background.

Results........

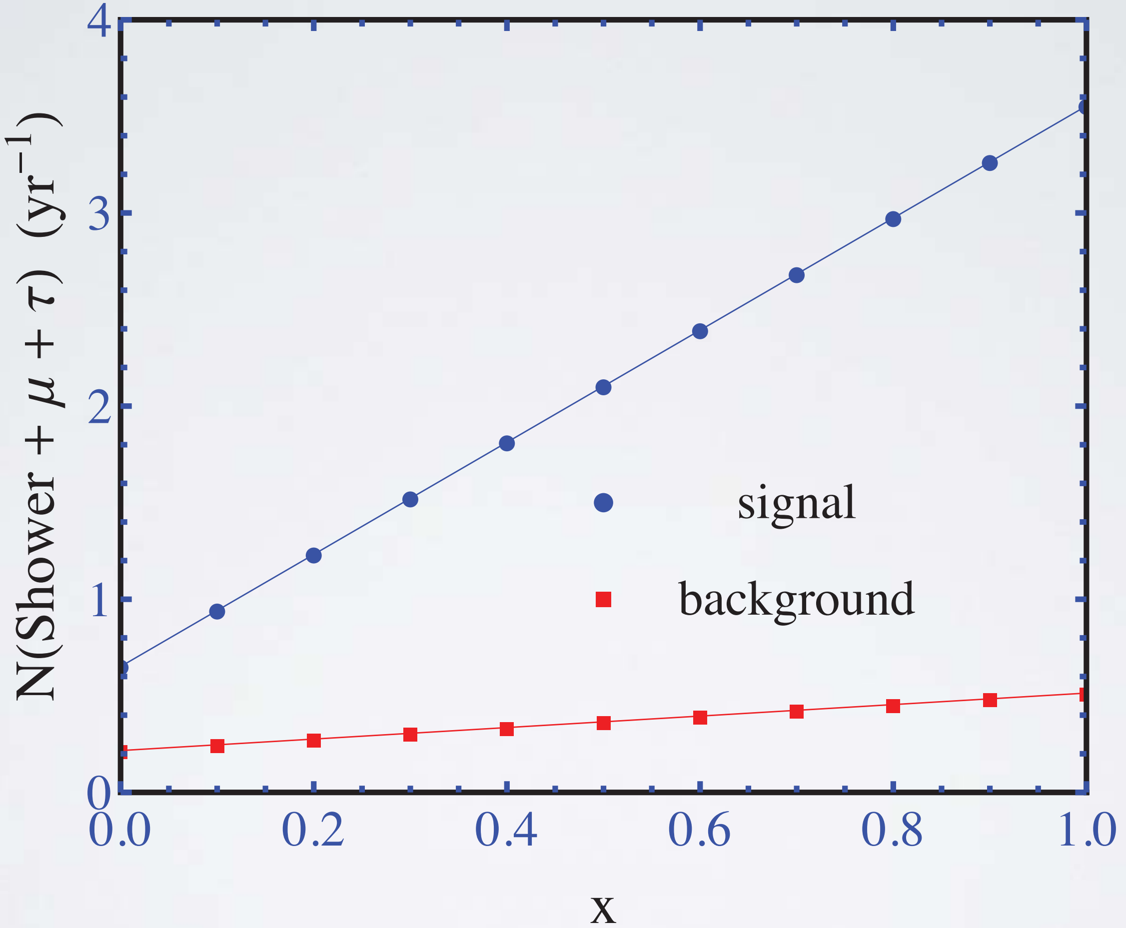
Add conventional shower, resonant shower, pure muon and contained vertex lollipop to compute total signal

x	(Conventionalshower)	GR	Total
0.0	0.21	0.65	0.86
0.5	0.4	2.1	2.5
1.0	0.5	3.6	4.1

1

20, 12 and 4 events in Icecube in 5 years required to see signal from resonance depending on the relative abundance of p-gamma and p-p sources.

Signal (GR) to Background (non-resonant) comparison..........



S/B rises from 3 at x=0 to 7 at x=1

The GR and Physics beyond the SM

Due to its sensitivity to electron-antineutrinos, can the GR can provide a testing ground for some scenarios of BSM physics

Consider neutrino decay with normal hierarchy, where nu_3 and nu_2 are unstable and decay to nu_1

Then, a neutrino produced say, via a $W^{\mu}\overline{\nu}_i\gamma_\mu l_\beta$ vertex has a spectral flux

$$F^{\beta}_{\nu_i} = |U_{\beta i}|^2 A E^{-2},$$

Detection occurs via production of a charged lepton of flavour alpha, leading to

$$F^{\beta}_{\nu_\alpha} = |U_{\alpha 1}|^2 |U_{\beta 1}|^2 A E^{-2}$$

In the decay scenario under consideration, the full flavour spectrum for a given species is

$$F_{\nu_\alpha} = \sum_{\beta} \phi_\beta \, |U_{\alpha 1}|^2 |U_{\beta 1}|^2 A E^{-2}.$$

where

$\phi_\beta = (1, 2, 0)$ for pp sources, for instance

Thus $F_{\nu_e}/F_{\nu_\mu} = |U_{e1}|^2/|U_{\mu 1}|^2 \simeq 4.$

Beacom, Bell, Hooper, Pakvasa & Weiler

which is significantly different from the expected value of 1 independent of ϕ_β

For the generalized flux for decay,one may write

Here ν_2 and ν_3 are unstable; $\nu_{3,2} \to \nu_1 X$ and $m_1 \ll m_2, m_3$,

$$E^2 F_{\nu_e}(\text{earth}) = 6 \times 10^{-8} |U_{e1}|^2 \left[x\, C_{pp}^{\nu_e} \frac{0.6}{6} + (1-x) C_{p\gamma}^{\nu_e} \frac{0.25}{3} \right],$$

$$C_{pp}^{\nu_e} = |U_{e1}|^2 + 2|U_{\mu 1}|^2 + \frac{1}{2} B_{2\to 1}(|U_{e2}|^2 + 2|U_{\mu 2}|^2) + \frac{1}{2} B_{3\to 1}(|U_{e3}|^2 + 2|U_{\mu 3}|^2),$$

$$C_{p\gamma}^{\nu_e} = |U_{e1}|^2 + |U_{\mu 1}|^2 + \frac{1}{2} B_{2\to 1}(|U_{e2}|^2 + |U_{\mu 2}|^2) + \frac{1}{2} B_{3\to 1}(|U_{e3}|^2 + |U_{\mu 3}|^2), \quad \text{(A.1)}$$

$$E^2 F_{\bar{\nu}_e}(\text{earth}) = 6 \times 10^{-8} |U_{e1}|^2 \left[x\, C_{pp}^{\bar{\nu}_e} \frac{0.6}{6} + (1-x) C_{p\gamma}^{\bar{\nu}_e} \frac{0.25}{3} \right],$$

$$C_{pp}^{\bar{\nu}_e} = C_{pp}^{\nu_e},$$

$$C_{p\gamma}^{\bar{\nu}_e} = |U_{\mu 1}|^2 + \frac{1}{2} B_{2\to 1}|U_{\mu 2}|^2 + \frac{1}{2} B_{3\to 1}|U_{\mu 3}|^2, \quad \text{(A.2)}$$

The generalized fluxes for other flavours of nu and antinu are then related to the electron flavour by

$$F_{\nu_\mu}(\text{earth}) = \frac{|U_{\mu 1}|^2}{|U_{e1}|^2} F_{\nu_e}(\text{earth}),$$

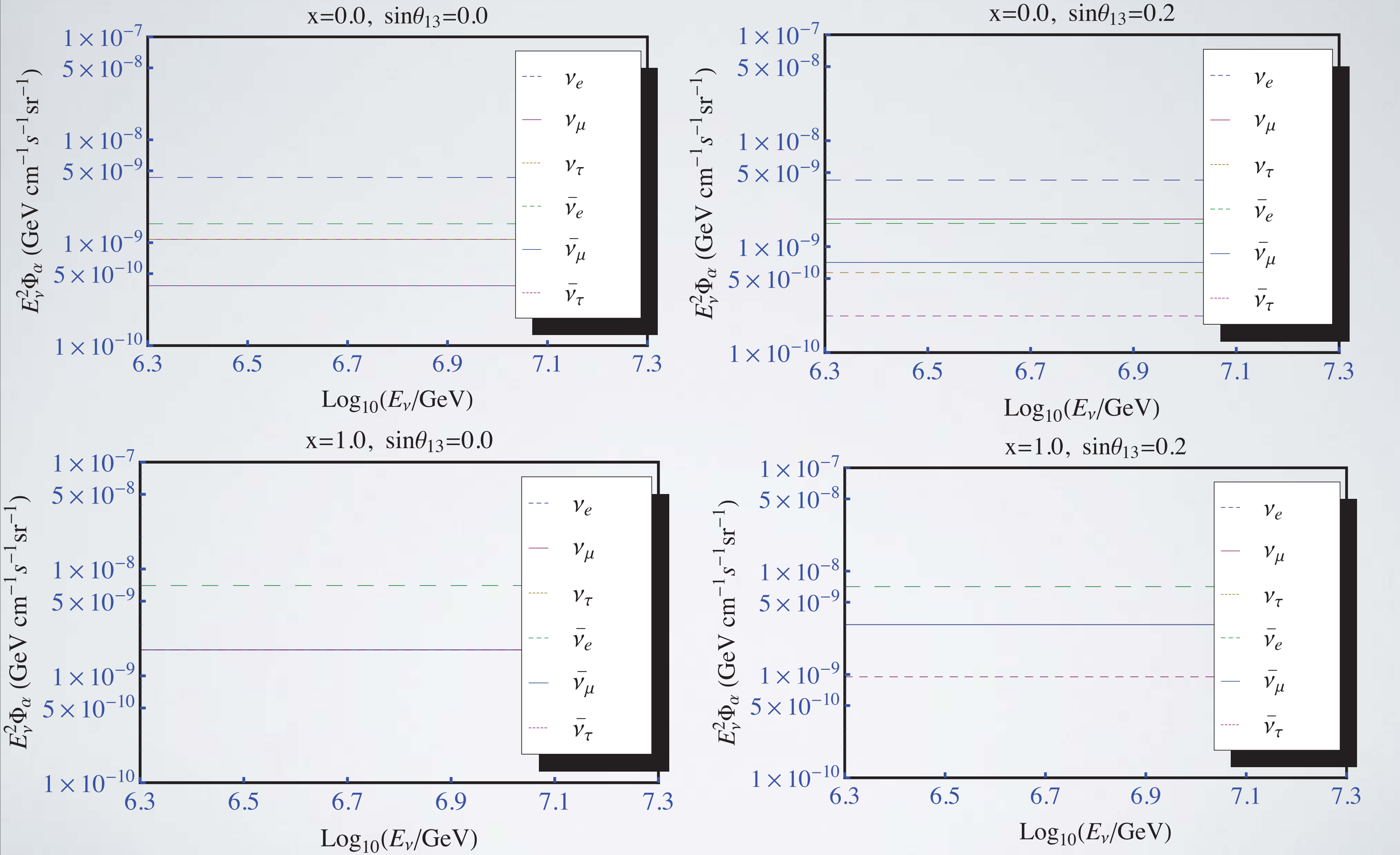
$$F_{\bar{\nu}_\mu}(\text{earth}) = \frac{|U_{\mu 1}|^2}{|U_{e1}|^2} F_{\bar{\nu}_e}(\text{earth}),$$

$$F_{\nu_\tau}(\text{earth}) = \frac{|U_{\tau 1}|^2}{|U_{e1}|^2} F_{\nu_e}(\text{earth}),$$

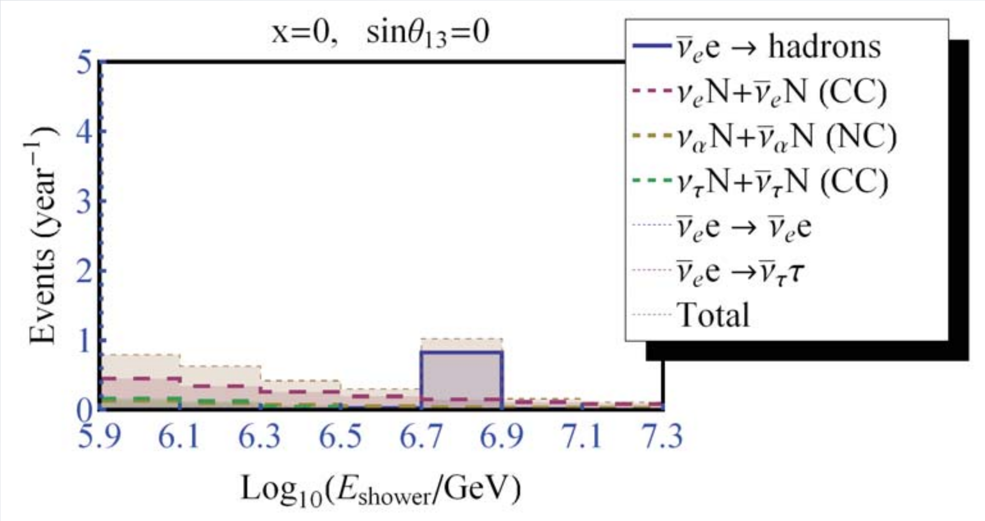
$$F_{\bar{\nu}_\tau}(\text{earth}) = \frac{|U_{\tau 1}|^2}{|U_{e1}|^2} F_{\bar{\nu}_e}(\text{earth}).$$

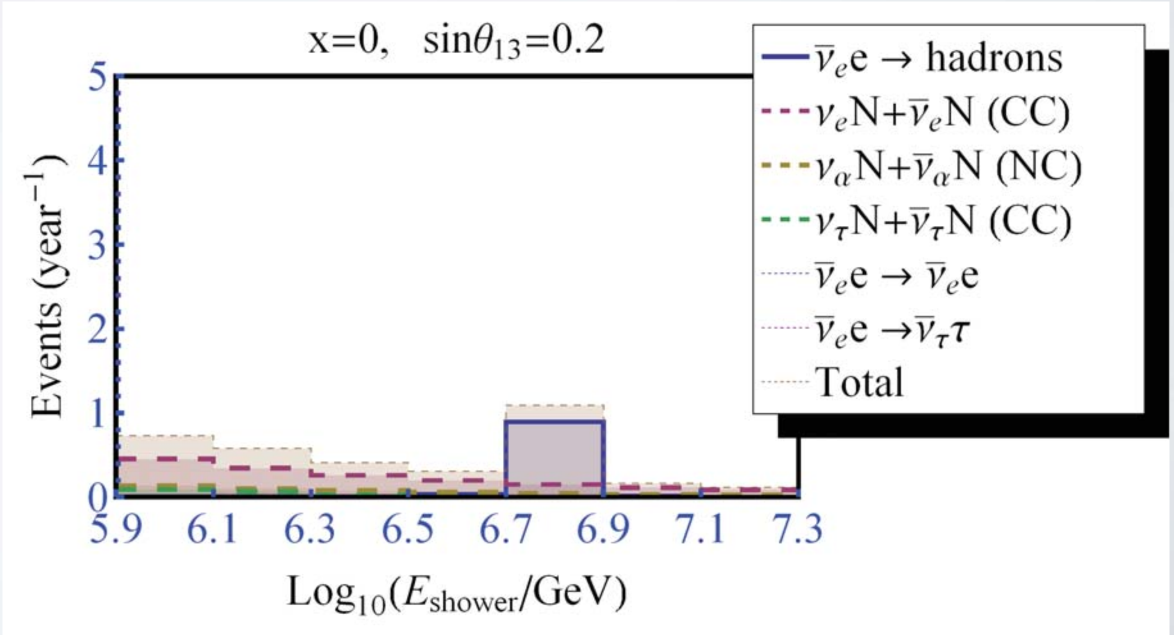
We note that the flavour ratios are independent of both x and decay branching ratios B

Decay fluxes……

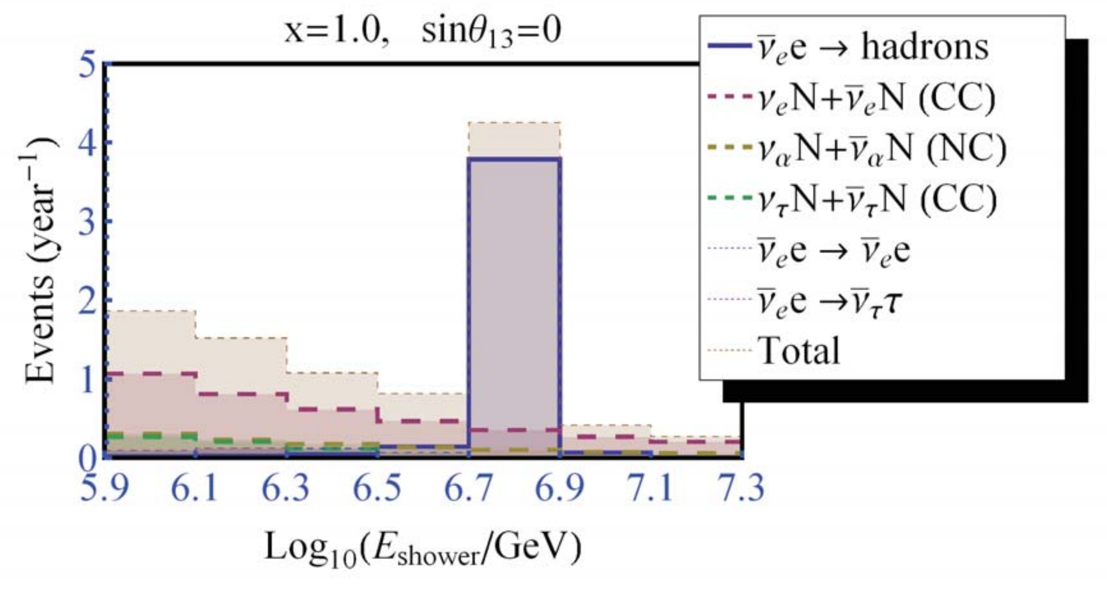


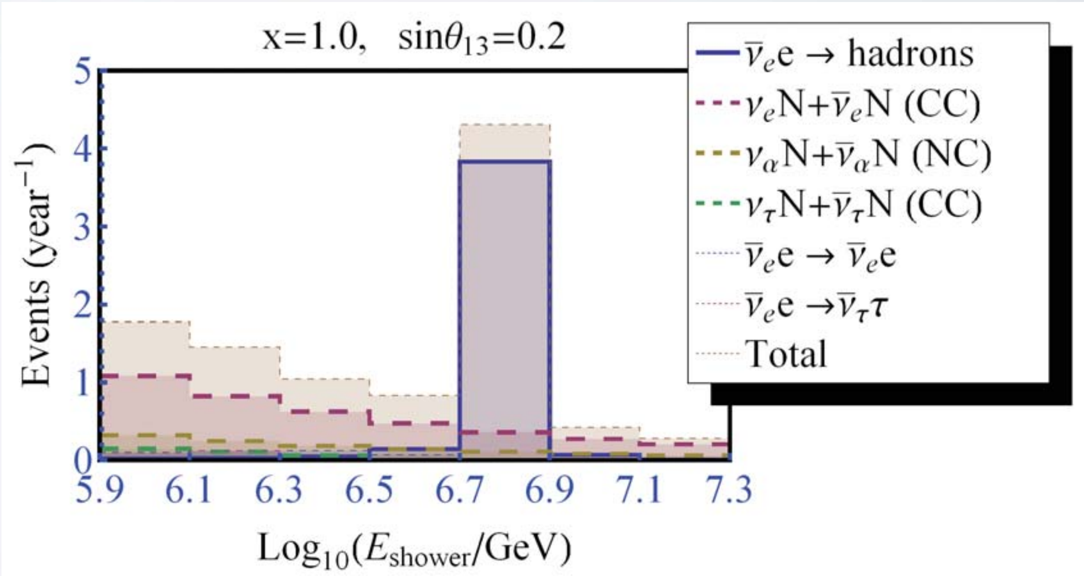
NH Decay Event Rates in the GR neighbourhood



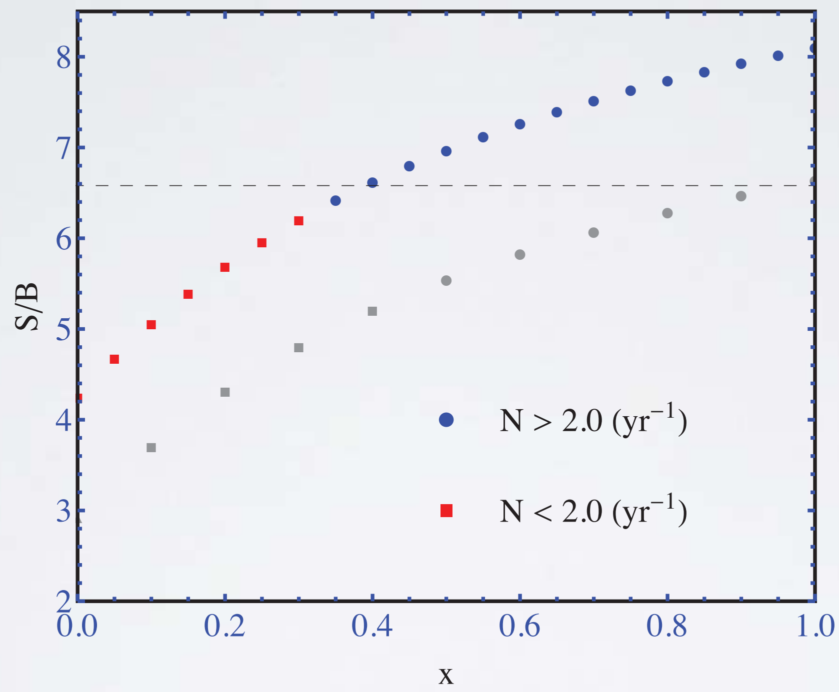


NH Decay Event Rates in the GR neighbourhood





S/B ratio for the decay scenario.........



Decay S/B depends on x but not on Branching ratios

(Not Seeing) UHE Neutrino Fluxes and Physics beyond the SM...........

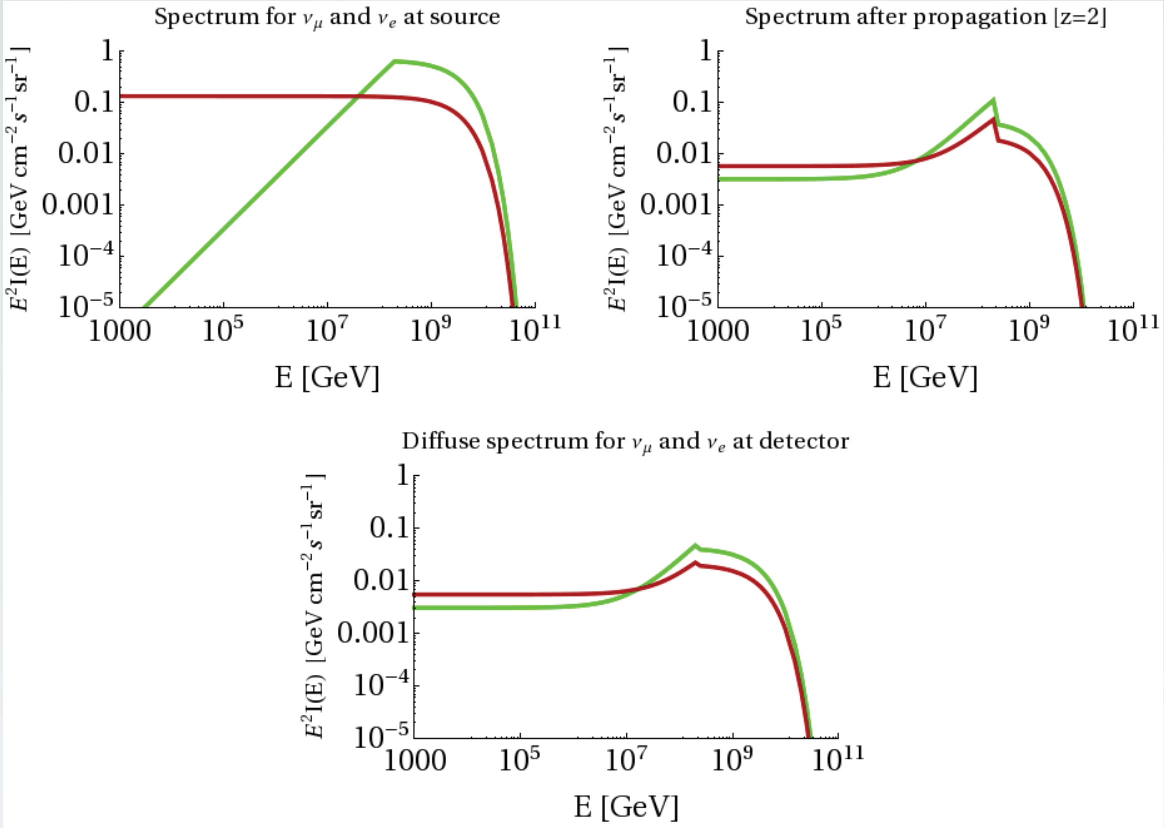
Our predictions of UHE fluxes at Earth depend, among other things, on oscillation probabilities based on SM physics.

Non-standard physics which affects the oscillation probabilities at propagation distances and energies relevant to UHE neutrinos will alter the fluxes we expect to observe.

This will alter the flavour ratios and event rates, sometimes very significantly.

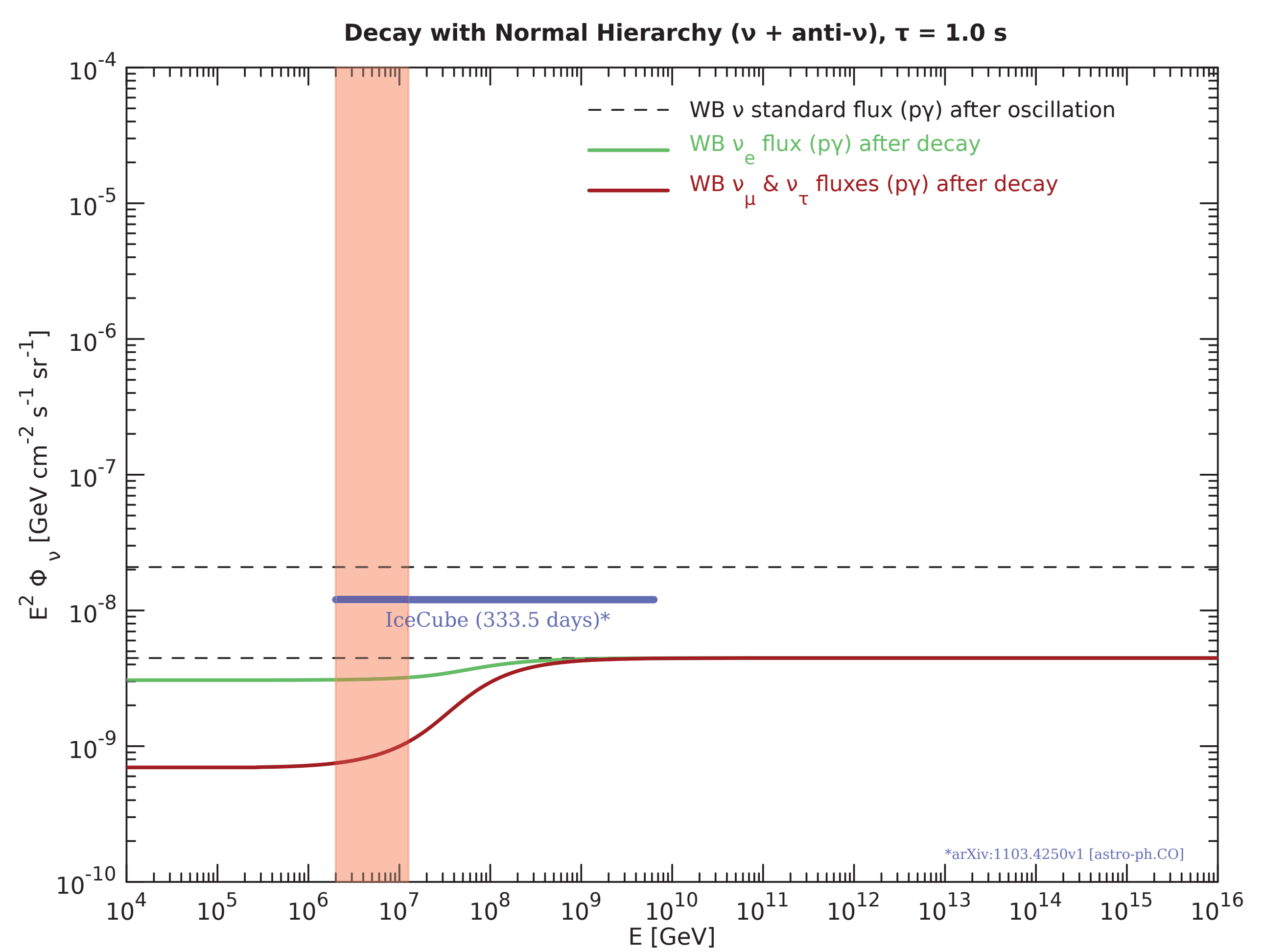
The WB bound for each flavour can be used to study such changes

Spectra at source versus spectra at Earth............



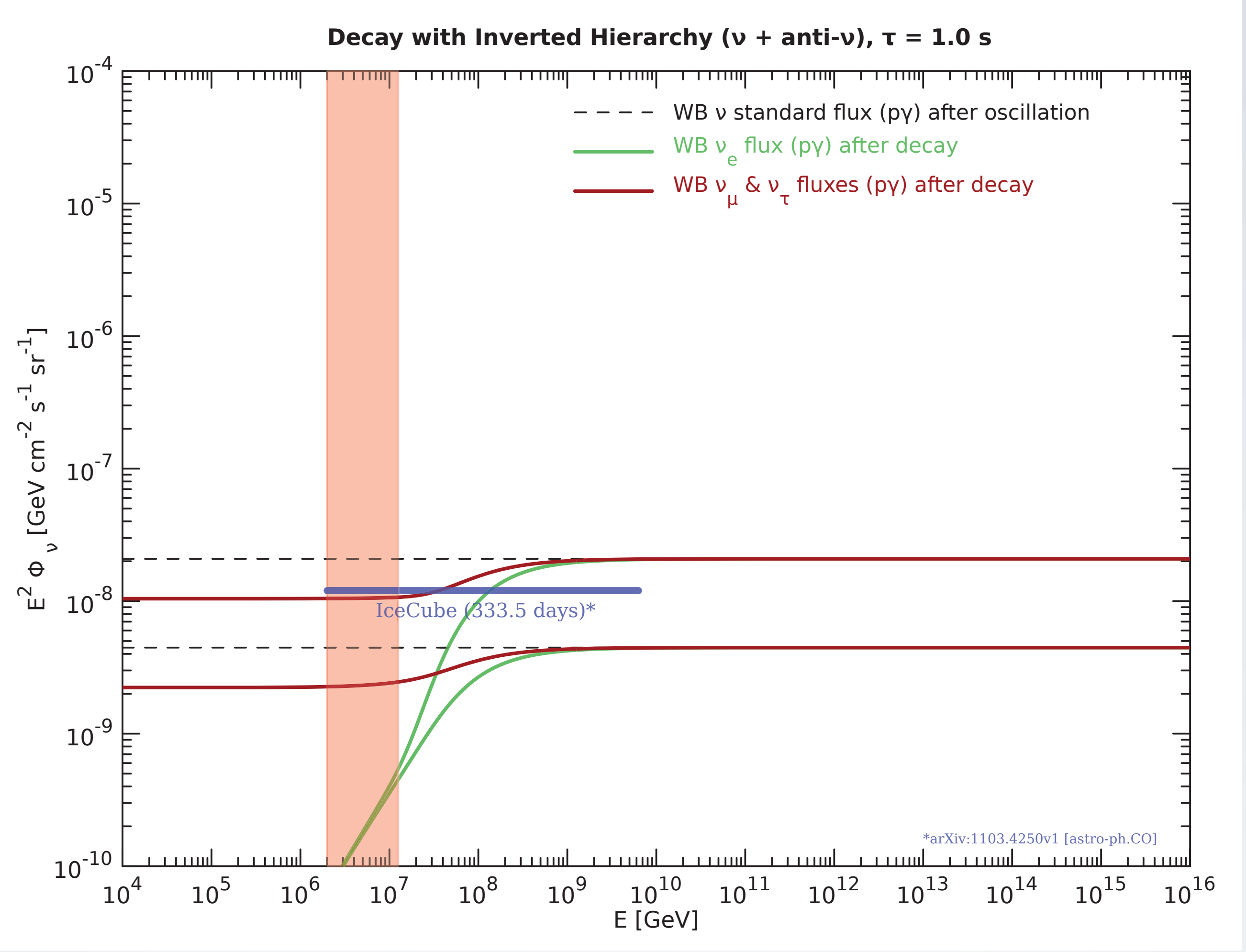
Oscillations wash out spectral differences at source

Simple Decay Scenario with Normal Hierarchy,



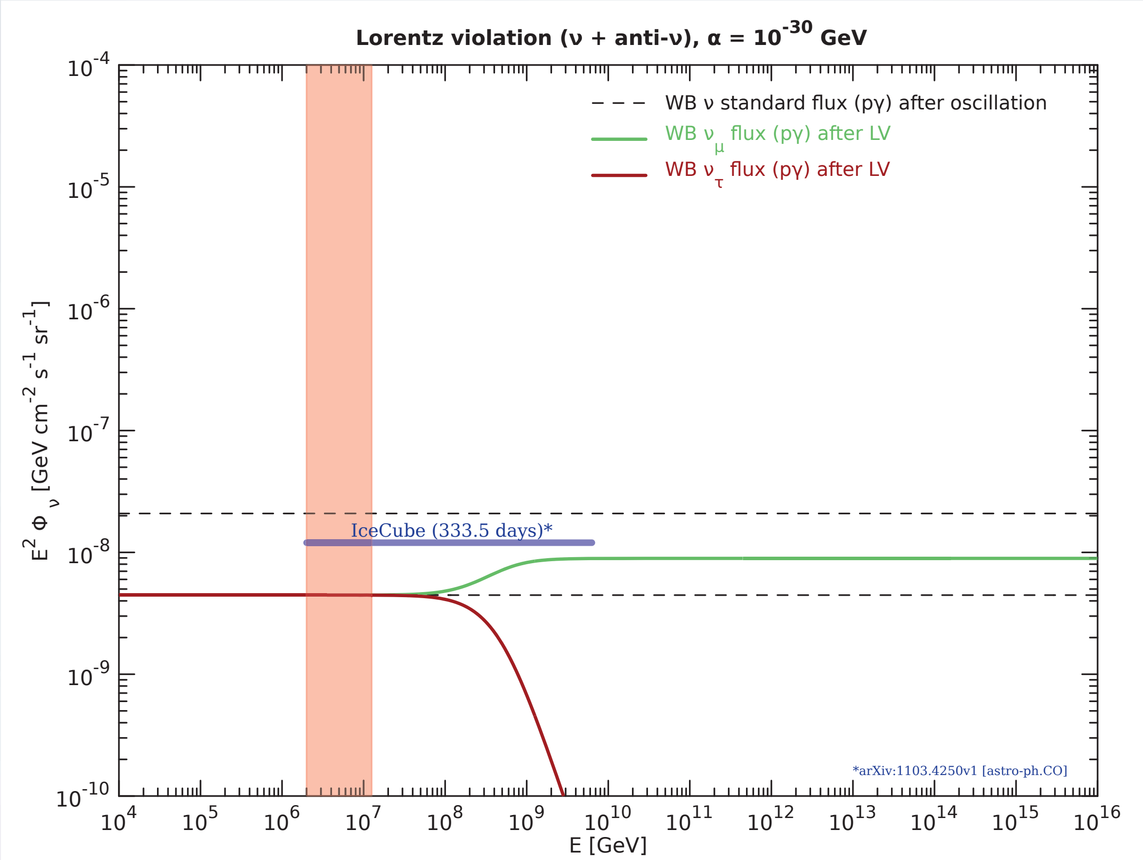
Depletion of nu_mu and nu_e fluxes with subsequent rise

Simple Decay Scenario with Inverted Hierarchy,



Effects (events, ratios etc) depend on hierarchy

Changes in the WB bound for mu and tau flavours due to Lorentz Violation.......



Total disappearance of tau neutrinos above a certain energy.

Conclusions....

Icecube limits on X-Galactic UHE neutrinos have grown progressively more stringent and have made neutrino astronomy a game of very small numbers.

The Glashow resonance is a small but potentially important region which should be explored as a discovery tool for these fluxes. It seems positioned in the right energy regime given the present situation.

While the quest to understand the nature of astrophysical sources via neutrino detection is the paramount goal, it should be kept in mind that non-standard physics during propagation may affect event ratios and flavour ratios non-trivially even though sources may be "standard".